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Enhanced Charmless Yield in B Decays and Inclusive B-Decay Puzzles

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Our analysis suggests that the charmless yield in B decays is enhanced over traditional estimates. The $c\bar{c}$ pair produced in $b \to c\bar{c}s$ transitions may be seen significantly as light hadrons due to non-perturbative effects. Existing data samples at $\Upsilon(4S)$ and Z^0 factories allow key measurements which are outlined.

1 Motivation

One prime motivation for optimizing our understanding of inclusive B decays is CP violation. CP asymmetries at the 50% level are predicted for the time-evolved $B_d \to J/\psi K_S$ decays [1], within the CKM model. The few hundred reconstructed $J/\psi K_S$ events [2] would thus allow meaningful CP studies, once they are tagged. Tagging denotes distinction of an initially pure B_d and $\overline{B}_d$. An optimal tagging algorithm combines self-tagging [3,4,2] with all available information from the other b-hadron decay [5]. Thus inclusive b-hadron decays must be understood. Such an understanding would enhance CP studies with B samples both inclusive [6] or exclusive. It would reduce backgrounds for any B-decay under study. Intriguing hadronization effects may be discovered [7].

2 Traditional Puzzles

The b is known to decay normally to a c, and that charm flavor is referred to as "right" charm. In contrast, the $b \to \bar{c}$ process produces "wrong" charm. The penguin amplitudes give rise to $b \to s$ transitions, which are seen as a kaon, additional light hadrons, and possibly additional $K\overline{K}$ pairs. Due to the small $|V_{ub}/V_{cb}| \sim 0.1$, the $b \to u$ transitions are negligible at the present level of accuracy. Theory calculates the rates for $b \to c\ell\bar{\nu}$ [8], $b \to c\bar{c}s$ [9,10,11], and the ratio of rates [9]

$$r_{ud} \equiv \frac{\Gamma(b \to c\bar{u}d')}{\Gamma(b \to ce\bar{\nu})} = 4.0 \pm 0.4\,. \tag{1}$$

The CKM parameters cancel in the ratio. The phase-space factor cancels in leading order and r_{ud} would be 3 because of color counting. QCD corrections (complete to next-to-leading-order with finite charm quark masss) have been found to enhance this ratio to 4.0 [9]. Of course we are not dealing with freely

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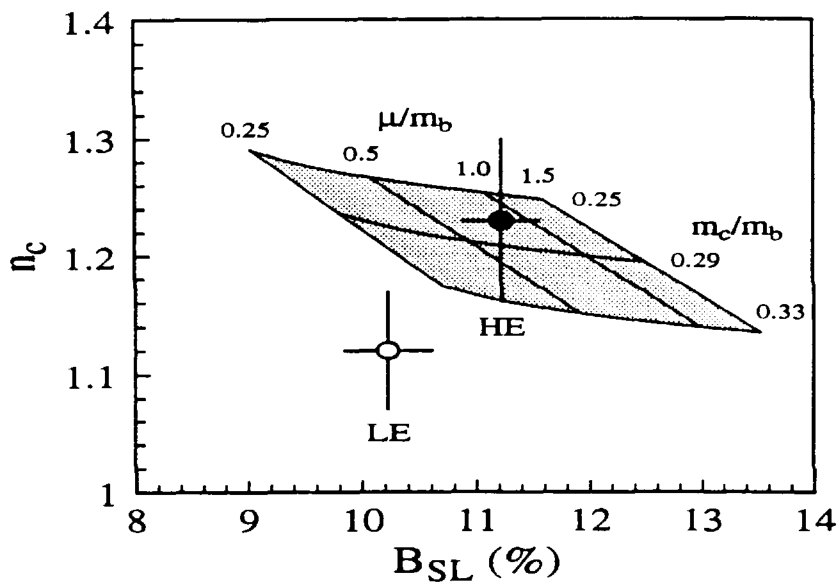

Figure 1: Theoretical prediction for the semileptonic branching ratio and charm multiplicity. The data points show the average experimental values obtained at $\Upsilon(4S)$ (LE) and Z^0 (HE) factories. Figure taken from Ref. [12].

decaying b-quarks, but with decays of b-hadrons. It must thus be emphasized that the calculation of r_{ud} assumes local quark-hadron duality.

In this talk, b denotes the weighted average of produced $\overline{B}$ mesons. The semileptonic BR is

$$BR_{sl} \equiv \Gamma(b \to Xe^-\overline{\nu})/\Gamma(b \to \text{all}), \tag{2}$$

and the charm multiplicity $\overset{(-)}{c}$ per b decay is given by

$$n_c = \frac{\#\overset{(-)}{c}}{\#b} = 1 - B(b \to \text{no charm}) + B(b \to c\bar{c}s')\ . \tag{3}$$

The current theoretical status is summarized in Fig. 1 [12,13], which plots the theoretically allowed (n_c, BR_{sl}) region.

The low (high) horizontal curve is for a large (small) m_c/m_b ratio. The diagonal curves are given for various renormalization scales. The left boundary is given by $\mu/m_b = 0.25$, for which $r_{ud} \gtrsim 5$, see Figure 2.

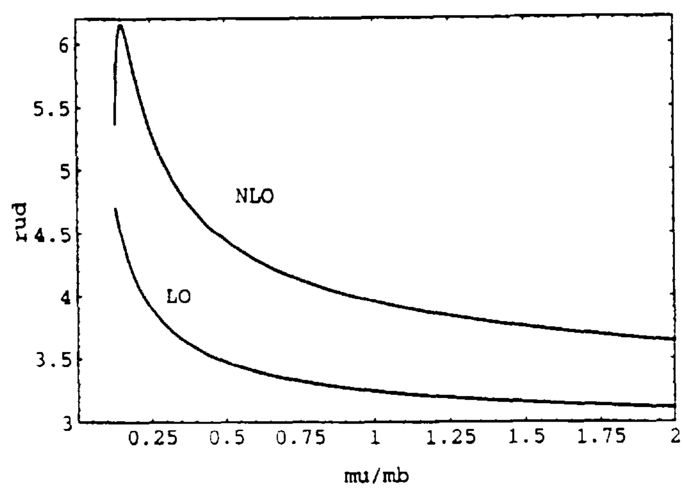

Figure 2: Scale dependence of r_{ud} for leading-order (LO) and next-to-leading-order (NLO) approximations[9]. Figure taken from Ref. [17].

The measured charm multiplicity per B decay n_c (as summarized in Fig. 1) must be revised downward significantly, because of several reasons. First, the measured central value of Ξ_c production is too large. An upper-limit has been derived and is drastically smaller[14]. The drastic reduction can be traced back to a large enhancement in the absolute BR scale of Ξ_c decays, a conclusion supported by recent work of Voloshin[15]. Second, the world-average for

$$B(\Lambda_c \to pK^- \pi^+) = 0.044 \pm 0.006 \tag{4}$$

must be sizably revised upward to 0.08 ± 0.02[14,16]. This causes n_c to decrease more significantly at Z^0-factories (because of Λ_b production) than at $\Upsilon(4S)$ factories.

However, n_c and $BR_{s\ell}$ are not the only observables. With the recent flavor specific measurement of wrong-sign $\overline{D}$ [$\overline{D}^0$ or D^-] production in b decay, $B(b \to \overline{D})$, the quantity r_{ud} can now be experimentally extracted,

$$r_{ud}[\text{exp.}] = \frac{B(b \to \text{open } c) - B(b \to \text{open } \bar{c}) + B(b \to u\bar{c}s')}{BR_{s\ell}} - 2 - r_\tau \,, \tag{5}$$

with minimal theoretical input, including[17,18]

$$B(b \to u\bar{c}s') = 0.0035 \pm 0.0018, \text{ and} \tag{6}$$

$$r_\tau = 0.22 \pm 0.02\,. \tag{7}$$

Using CLEO data alone $r_{ud}[\text{exp.}] = 4.1 \pm 0.7$ [17].

The sizable $b \to \overline{D}$ observation unearthed an overlooked background $b \to \overline{D} \to \ell^-$ in model-independent, inclusive $BR_{s\ell}$ measurements[14]. The Z^0 measurement will be reduced significantly, and is more affected than the $\Upsilon(4S)$ measurements because of differences in cuts on the signal lepton momentum. The model-independent extraction of $BR_{s\ell}$ requires the removal of $B^0 - \overline{B}^0$ mixing effects and the value of the average mixing parameter $\overline{\chi}$ as input. But both the value of $\overline{\chi}$ and the removal of $B^0 - \overline{B}^0$ mixing effects will have to be modified, because the secondary leptons $b \to \overset{(-)}{c} \to \ell$ experience different mixing than the primary leptons $b \to \ell^-$ [14]. We anticipate [14] that reanalyses of data will significantly reduce the difference between the $BR_{s\ell}$ measurements from the Z^0 and $\Upsilon(4S)$ environments in favor of the lower $\Upsilon(4S)$ result [22].

After applying the revisions onto Fig. 1, the experimental measurements from $\Upsilon(4S)$ and Z^0 factories are consistent. The $\Upsilon(4S)$ data support a low renormalization scale μ, and are marginally consistent with theory based on the heavy quark expansion [13,12].

3 Flavor-Specific Input

CLEO[19] and ALEPH[20] determined

$$B(b \to \overline{D}) = \begin{cases} 0.085 \pm 0.025 & \text{CLEO} \quad 1996 \\ 0.145 \pm 0.037 & \text{ALEPH} \quad 1996 \end{cases} \tag{8}$$

Do those measurements confirm the prediction [21] of $B(b \to \overline{D}) \sim 0.2$?

To answer that question, a synthesis of all available data, flavor-specific and flavor-blind, was in order. The $B(b \to \text{no open charm})$ is that fraction of $\overline{B}$ decays which has no weakly decaying charm, that is, no separate charm vertex. It can be inferred indirectly [17]:

Method A:

$$B(b \to \text{no open charm}) = 1 - B(b \to \text{open } c) - B(b \to u\bar{c}s'). \tag{9}$$

Method B:

$$B(b \to \text{no open charm}) = R - B(b \to \text{open } \bar{c})\,. \tag{10}$$

Table 1: Indirect estimates of no open charm in B decays[17]

Method	$B(b \to \text{no open charm})$ [CLEO]
Method A	0.15 ± 0.05
Method B	0.17 ± 0.06
Method C	0.16 ± 0.04

Here, R is the remaining BR after reliable components have been subtracted,

$$\begin{aligned} R &\equiv B(b \to \text{no charm}) + B(b \to c\bar{c}s') + B(b \to u\bar{c}s') = \\ &= 1 - B(b \to c\ell\bar{\nu}) - B(b \to c\bar{u}d') = \\ &= 1 - BR_{s\ell}[2 + r_\tau + r_{ud}] \,. \end{aligned} \tag{11}$$

Theory provides r_τ [18], r_{ud} [9], experiment $BR_{s\ell} = 0.105 \pm 0.005$[22], and $R = 0.35 \pm 0.05$ results. This result changes only minimally to

$$R = 0.36 \pm 0.05, \tag{12}$$

once differences in the B^- and $\overline{B}_d$ rates governed by $b \to c\bar{u}d$ have been conservatively incorporated [13,23]. Our prediction Eq. (12) for R combines the most accurate information available from both theory and experiment [17].

The average of methods A and B is denoted by Method C:

$$B(b \to \text{no open charm}) = \frac{1}{2}[1 + R - Y_{\text{open } c} - B(b \to u\bar{c}s')], \tag{13}$$

where the flavor-blind quantity $Y_{\text{open } c} \equiv B(b \to \text{open } c) + B(b \to \text{open } \bar{c})$. Because flavor-blind yields are better known than flavor-specific ones, Method C allows the most accurate prediction for $B(b \to \text{no open charm})$. Note that while Method A involves experimental data alone (with minimal theoretical input), Methods B and C require the theoretical prediction for r_{ud}. Method C reduces its sensitivity on theoretical input with regard to Method B, because of the factor 1/2. Table I summarizes our findings [17].

Why is $B(b \to \text{no open charm})$ enhanced over traditional expectations of 0.05 ± 0.01 [17]. New physics may provide a solution and could enhance the charmless $b \to s'$ transitions[24]. But before concluding that, all Standard Model explanations must be exhausted first.

Non-perturbative effects could be responsible for $c\bar{c}$ pairs to be seen significantly as light hadrons. The $c\bar{c}$ pairs produced in $b \to c\bar{c}s$ transitions have low invariant mass and are dominantly in a color-octet state [25,17]. The predominantly $c\bar{c}$ color-octet configuration may have sizable overlap with the

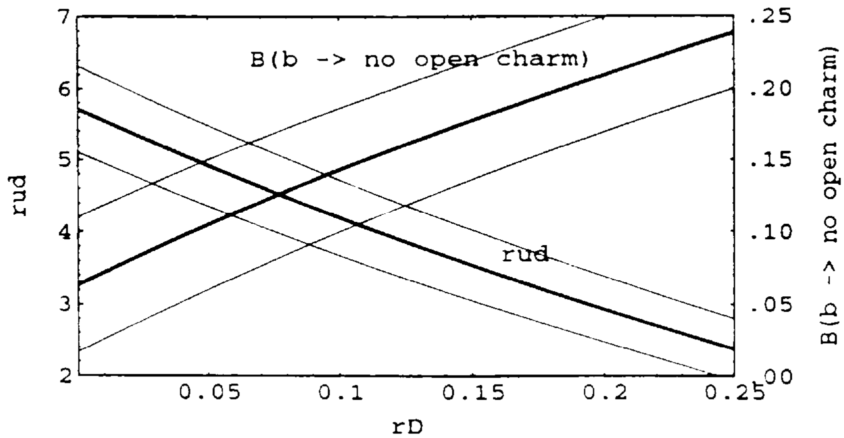

Figure 3: $B(b \to$ no open charm) and r_{ud} as functions of r_D [17].

wavefunction of $c\bar{c}$- hybrids, H_c, which are made of $c\bar{c}$ and glue[26,27,28,29,30]. Although their masses could be beyond the open charm threshold[26,29,30], model-dependent selection rules suppress $H_c \to D^{(*)}\overline{D}^{(*)}$ transitions[27,31]. Consequently, they could be narrow and could be seen sizably as light hadrons. That light hadron yield is probably governed significantly by resonant production of light gluonic hadrons[7]. More generally, because the b-quark is sufficiently massive and decays in a gluon rich environment (provided, for instance, by the soft gluons emanating from the light spectator quark[s]), we anticipate copious production of gluonic hadrons[7] and enhanced non-perturbative annihilation of $c\bar{c}$ pairs (see Figure (1b) in Ref.[32]).

Perhaps the wavefunctions of light hadrons [$\pi, \rho, K^{(*)}$, etc.] have a non-negligible component of intrinsic $c\bar{c}$[33,34]. The generic charmless mode is $\overline{B} \to \overline{K} n\pi$ ($n \geq 1$), where no partial subset of final state particles reconstructs a charmed hadron. The $c\bar{c}$ component may have transformed itself into an intrinsic piece of decay products, and interference effects may be important[35]. Because more excited light resonances have generally a larger intrinsic charm component than less excited states[35], it appears plausible that the $\overline{B} \to \overline{K} n\pi$ processes feed through such more excited resonances.[a] The end result of such

[a] We expect those resonances to have net zero strangeness, else the whole invariant mass m_b of the $b \to c\bar{c}s$ process would be available to create strange resonances with intrinsic charm.

a scenario is very similar to the above mentioned possibility of charmed hybrid production. Nevertheless, they could be distinguished.

Charmed hybrids are predicted [26,29,30] to have masses of about 4 GeV or above, while light resonances with an intrinsic $c\bar{c}$ component could be significantly lighter. Consequently, a detailed momentum spectrum of the recoiling $K^{(*)}$ in such B decays may help in differentiating the various possibilities. A surplus of very high momentum $K^{(*)}$ is consistent with the production of excited resonances that contain intrinsic charm or with direct production of light gluonic hadrons. A high momentum $K^{(*)}$ excess (although less high than the aforementioned) may indicate H_c production, while the momentum spectra of produced kaons in non-resonant $\overline{B} \to \overline{K} n\pi$ processes will be different. Such and other non-perturbative effects must be carefully investigated.

Another solution is provided by a reduction of $B(D^0 \to K^-\pi^+)$ from presently accepted values, which would increase n_c and would cause $B(b \to$ no open charm) to decrease towards traditional expectations [14,36]. This and other systematic effects have been discussed in Ref. [17].

Figure 3 emphasizes the importance of accurate measurements of

$$r_D \equiv \frac{B(b \to \overline{D})}{B(b \to D)} \; . \tag{14}$$

That figure plots $B(b \to$ no open charm) (Method A) and r_{ud} as a function of r_D using essentially only experimental input.

The ALEPH measurement fully reconstructs both charm mesons in $\overline{B} \to D\overline{D}X$ transitions, and thus suffers from low statistics [20]. The existing data samples at Z^0-factories allow more accurate $B(b \to \overline{D})$ measurements. After selecting an enriched b-sample, one needs to reconstruct a <u>single</u> $\overset{(-)}{D}$ only, employ optimized flavor-tagging, and correct for $B^0 - \overline{B}^0$ mixing effects. (We add parenthetically that those data samples allow meaningful CP violating tests [6].) If sizable charged $B^\pm$ data samples can be efficiently isolated, one could determine again $B(B^- \to \overline{D}X)$ and $B(b \to \overline{D})$ without the need for a flavor-tag and for corrections due to $B^0 - \overline{B}^0$ mixing. The accurate determinations of $B(b \to \overline{D})$ are crucial for resolving the inclusive B decay puzzles (see Figure 3), and should be pursued with high priority.

4 Conclusions

Under the traditional assumption of a tiny $B(b \to$ charmless), the accurately measured $BR_{s\ell} = 0.105 \pm 0.005$ [22] allowed the prediction [21]

$$n_c = 1.30 \pm 0.05 \; , \tag{15}$$

while experimentally [37]

$$n_c = 1.10 \pm 0.05 \ . \tag{16}$$

Recent flavor-specific measurements opened up new aspects pertaining to this puzzle and allowed the indirect extraction of $B(b \to \text{no open charm})$ in a variety of ways. The results of the methods are consistent, strengthening our conclusion that the charmless yield in B decays is enhanced over traditional estimates. Method C yields the most accurate prediction of

$$B(b \to \text{no open charm}) = 0.16 \pm 0.04 \ . \tag{17}$$

This large charmless yield would show up as an enhanced fraction of b-decays, without a separate daughter charm vertex. We expect the underlying physics to be non-perturbative in nature, which causes a sizable fraction of $c\bar{c}$ pairs to be seen as light hadrons. The momentum spectrum of the involved $K^{(*)}$ may help in distinguishing among the various scenarios.

We touched upon the systematics of our analysis and considered the parameters $[B(b \to \text{no open charm}), r_{ud}, B(D^0 \to K^-\pi^+), r_D]$ and correlations among them [17]. The prediction for r_{ud} involve larger theoretical uncertainties than presently realized [17]. [Under the assumption of local duality, the dependence of the predicted r_{ud} on the scale μ is large, and is not improved by going from leading-order to next-to-leading-order, see Figure 2. While the large scale dependence is troublesome, an even more disturbing aspect is the fact that duality assumes an inclusive rate based on 3 body phase-space, while the $b \to c\bar{u}d$ transitions proceed sizably as quasi-two body modes.[b]] Fortunately, r_{ud} can be extracted from experimental measurements alone, which can be confronted with theory. More accurate determinations of r_D or equivalently $B(b \to \overline{D})$ are possible from existing data samples at LEP/SLD/CLEO. They are invaluable in guiding us toward a more complete understanding of B-decays.

[b] The $b \to c\bar{u}d$ transitions could be modelled as follows. For small invariant $\bar{u}d$ masses $(m_{\bar{u}d} \leq m_\tau)$, the color-singlet $\bar{u}d$ pair hadronizes with little or no final state interactions. The factorization assumption can be justified, because by the time the $\bar{u}d$ forms a sizable color dipole [with which it could interact with its surrounding environment], it left the other debris of the B-decay far behind [38]. The hadronization of those $\bar{u}d$ pairs can be determined from the well-studied τ decays, $\tau \to \nu + \bar{u}d$, which are dominated by the production of $\bar{u}d$ resonances. The $b \to c$ transitions can be modelled by HQET with input from semileptonic measurements and are seen dominantly as (D, D^*, D^{**}) resonances. Factorization is not as reliable for higher invariant $\bar{u}d$ masses. Fortunately, the $\bar{u}d$ invariant mass spectrum falls rapidly off at higher masses, as shown by a straightforward Dalitz plot. Assuming factorization, the vector contribution can be inferred from e^+e^- measurements at the same c.m. energy, where the isospin 1 component has to be isolated from the data. The axial-vector component can be obtained from the relevant spectral function. We are in the process of developing a $b \to c\bar{u}d$ Monte Carlo simulation [39].

B decays are a fertile ground for searching and discovering subtle hadronization effects. By utilizing the long lifetime of b-hadrons, vertex detectors can drastically reduce backgrounds. To fully explore multibody decays of b-hadrons it will be essential to not only have good $\pi/K/p$ separation, but the ability to detect $\pi^0, \eta^{(\prime)}, \gamma$ as well. An additional very important bonus will be a more optimal exploration of sizable CP violating effects residing in such multi-body B decay modes. Especially striking effects within the CKM model are expected in $b \to d$ transitions.

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